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THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

Morbidities Calculation: Guidelines and Walkthrough

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Background

Morbidity is the experience of poor health or disease. Analyses of the health risks of air pollution often focus on early death, but the inclusion of morbidities provides a more comprehensive view and includes impacts experienced by more people. Although the estimated value of reducing risk of early death (expressed as the Value of a Statistical Life, or VSL) is often very high compared to the value placed on preventing morbidities [see figure 1], the inclusion of morbidities broadens the analysis and may engage specific interest groups, such as those involved in improving children's health or helping asthma sufferers.

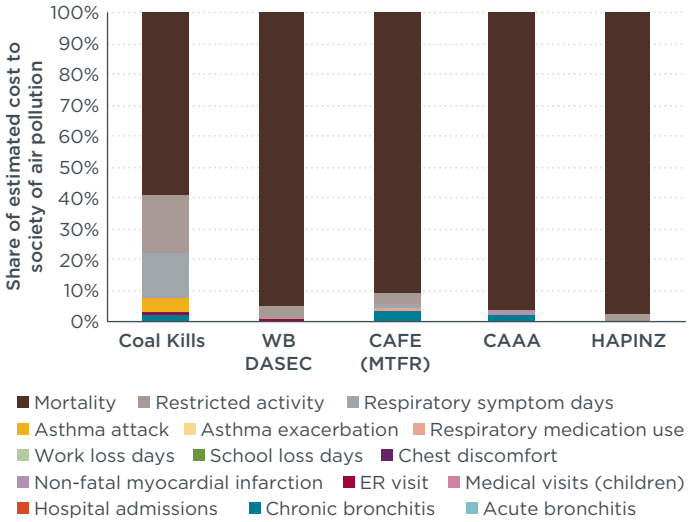

Figure 1: Cross-study comparison of the health costs contributed by mortality risk compared to morbidity risk. Coal Kills[1] and World Bank Diagnostic Assessment of Select Environmental Challenges (WB DASEC)[2] evaluate air pollution health risks in India, while Clean Air For Europe (CAFE)[3] evaluates risk in the EU, Clean Air Act Amendment (CAAA) study[4] evaluates risk in the U.S. and Health and Air Pollution in New Zealand (HAPINZ) study[5] evaluates risk in New Zealand.

Morbidity endpoints evaluated in publicly available health impact assessments reviewed for this memo fall into three broad categories: ***Medical Visits & Acute Illness***, including hospital admissions, emergency room visits, and non-fatal heart attacks; ***Bronchitis and Asthma***, including chronic bronchitis, acute respiratory symptoms, asthma exacerbation, and medication use; and ***Activity Effects***, including work loss days and restricted activity days. A more detailed description of many common endpoints is included in Appendix A. The health impacts of air pollution is an evolving field of research, and more endpoints are likely to be added to the list as more epidemiological evidence is collected and analyzed.

Morbidity estimates associated with vehicle emissions exposure use much of the same data as mortality estimates. An additional requirement is the collection of baseline rates for all morbidity endpoints considered. Estimating these rates in developing countries is often very challenging and research-intensive. In the absence

1 Goenka D and Guttikunda S. (2013). COAL KILLS: An Assessment of Death and Disease caused by India's Dirtiest Energy Source. Retrieved from http://www.greenpeace.org/india/Global/india/report/Coal_Kills.pdf

2 World Bank. (2013). An analysis of physical and monetary losses of environmental health and natural resources. Vol 1 of India—Diagnostic assessment of select environmental challenges. Washington DC; World Bank. Retrieved from http://documents.worldbank.org/curated/en/2013/06/18009327/india-diagnostic-assessment-select-environmental-challenges-vol-1-3-analysis-physical-monetary-losses-environmental-health-natural-resources

3 Commission of the European Communities. (2005) Annex to: The communication on Thematic Strategy on Air Pollution and The Directive on "Ambient Air Quality and Cleaner Air for Europe", Impact Assessment. Brussels.

4 U.S. Environmental Protection Agency. (2011). The Benefits and Costs of the Clean Air Act from 1990 to 2020. Washington DC: US EPA.

5 Kuschel G et al. (2012). Updated Health and Air Pollution in New Zealand Study. Health Research Council of New Zealand. Retrieved from http://www.hapinz.org.nz/HAPINZ%20Update_Vol%201%20Summary%20Report.pdf.

of such local data, many studies assume baseline rates based on US or European studies (See Bell et al. 2006 in Latin America[6], Sakuliniyomporn et al. 2011 in Thailand[7], Rabl et al. 2011 in China[8], Hoveidi 2013 in Iran[9]). Concentration-response functions needed to estimate increase in morbidity risk are almost always taken from epidemiological studies conducted elsewhere such as the US, Canada, or Europe. Some studies have integrated local epidemiological research into their analyses[6,10].

For cost-benefit analysis, the costs associated with increases in morbidity risks can be assessed based on two approaches: Cost of Illness (COI) and Willingness to Pay (WTP). COI is based on the total costs of treatment, medication, and foregone wages or lost productivity, and does not include the intangible values like discomfort or suffering[6,10]. WTP, which is evaluated through surveys or other indications of the value placed on avoiding the risk of health damages (the average amount the public is willing to pay to prevent a medical issue), does theoretically include both the cost of illness and the value of avoiding discomfort or pain. WTP values are typically several times higher than COI; Bell et al. (2006) evaluated the economic impact of pollution-related morbidity using both COI and WTP values and found the ratio to range from 1:6.5 to 1:8.5. The transfer of either COI or WTP values from a US/EU context to a developing country and the projection of those values forward in time should be consistent with the metric and elasticity used to transfer VSL values. For further guidance on values transfer and the calculation of the net present value of all health benefits, please refer to ICCT guidance on cost-benefit analysis.

The following checklist and walk-through example serve as the basis for standard morbidity estimation for ICCT CBA, with data flexibilities and input sensitivities noted. The checklist assumes that standard methods have been followed to evaluate change in mortality risk. This includes developing baseline and counterfactual emissions scenarios, and estimating annual ambient $PM_{2.5}$ concentrations. It also includes assembling time-resolved data on the size of the exposed population and the share of the exposed population in different age categories (at minimum, those under the age of 5 and over the age of 35).

MORBIDITY CALCULATION CHECKLIST

1) **Choose set of endpoints. Appendix A provides a list of commonly-used endpoints to choose from.** *This choice may be informed by the valuation of each endpoint, the total cost estimate (the product of valuation and total occurrence, see Appendix C), specific interest in a particular endpoint category, or availability of baseline incidence rates. A balanced set of endpoints are demonstrated in the walk-through for the US.*

   a) **Note which age categories each endpoint applies to.**

   b) **Note endpoints with other restrictions, such as specific sensitive population or potential double-counting.**

      i) *Sensitive populations: Asthma attacks or exacerbation only occurs in the asthmatic population; this requires an estimate of asthma prevalence. American Lung Association gives an average prevalence of 129.1 out of 1,000 in the US in 2011, although rates vary by age category[11]. The International Study of Asthma and Allergies in Childhood (ISAAC) study, particularly Phase Three, may include better prevalence for children in developing countries[12]. New cases of chronic bronchitis can only occur in the population that does not already suffer from CB; this requires an estimate of CB prevalence. American Lung Association gives an average prevalence of 43.6 out of 1,000, although rates vary by age category[13].*

6 Bell, M. L., Davis, D. L., Gouveia, N., Borja-Aburto, V. H., & Cifuentes, L. A. (2006). The avoidable health effects of air pollution in three Latin American cities: Santiago, São Paulo, and Mexico City. *Environmental Research*, 100(3), 431–440.

7 Sakulniyomporn, S., Kubaha, K., & Chullabodhi, C. (2011). External costs of fossil electricity generation: Health-based assessment in Thailand. *Renewable and Sustainable Energy Reviews*, 15(8), 3470–3479.

8 Rabl, A. (2011, November 26). How to use The ExternE methodology in China. Retrieved from http://www.amse-aixmarseille.fr/sites/default/files/_valorisation/contrats/paper_4.1_rabl.pdf

9 Hoveidi, H. (2013). Cost Emission of PM_{10} on Human Health Due to the Solid Waste Disposal Scenarios, Case Study; Tehran, Iran. *Journal of Earth Science & Climatic Change*, 04(03).

10 Cifuentes, L. A., Krupnick, A. J., O'Ryan, R., & Toman, M. (2005). Urban Air Quality and Human Health in Latin America and the Caribbean (IDB Publications No. 25378). Inter-American Development Bank. Retrieved from http://ideas.repec.org/p/idb/brikps/25378.html

11 American Lung Association. (2012). Trends in Asthma Morbidity and Mortality. American Lung Association, Epidemiology and Statistics Unit, Research and Health Education Division. Retrieved from http://www.lung.org/finding-cures/our-research/trend-reports/asthma-trend-report.pdf

12 ISAAC Steering Committee. (2012). The International Study of Asthma and Allergies in Childhood. Auckland Medical Research Foundation. Retrieved from http://isaac.auckland.ac.nz/phases/phasethree/phasethree.html

13 American Lung Association. (2013). Trends in COPD (Chronic Bronchitis and Emphysema): Morbidity and Mortality. American Lung Association, Epidemiology and Statistics Unit, Research and Health Education Division. Retrieved from http://www.lung.org/finding-cures/our-research/trend-reports/copd-trend-report.pdf

ii) To avoid double counting, check description of disease including ICD-9 code to ensure that endpoints do not overlap. For example, if both non-fatal heart attacks (Acute Myocardial Infarction/AMI) and cardiovascular hospitalization are calculated, incidence of hospitalization from AMI should not be included in cardiovascular hospitalization calculation. For non-fatal heart attacks, care should be taken to avoid overlap with AMI mortality in baseline incidence data, as some fraction of AMI patients admitted to the hospital die. The US-based COBRA tool assumes a survival rate of 93% in calculating avoided cases of AMI[14].

2) For each endpoint, find the equation form and coefficient(s) for the concentration-response (C-R) function in Appendix B or BenMAP Manual Appendix D[15].

a) *There are often multiple studies for a single endpoint resulting in several options for coefficients. A single study may be chosen, or estimates from different studies may be pooled[16].*

b) *If a local or other epidemiological study is used that is not included in Appendix B, and the C-R function is not reported, see BenMAP Manual Appendix C for guidance on deriving a function from relative risk increase or odds ratio.*

3) For each endpoint find the baseline incidence rate (the number of cases of the endpoint per person and per year) for all required age categories.

a) *If local data is not available and the analysis has a narrow time scope or a comprehensive set of endpoints is desired, US or EU baseline rates can be assumed. This assumption should be stated in the CBA methods. As an additional resource, the Clean Air Program can provide a working Incidence Database that lists the assumptions found in CBA analyses.*

b) *Although disease incidence is expected to change over time with changing circumstances in medicine, economic development, climate, etc., it is not advised to include projected future changes in disease incidence unless they are of specific importance to the study because they introduce unexplained independent trends in health results. Changes due to demographic shifts will be reflected as the size of age category will change.*

4) If valuation is included, determine the COI or WTP value of each endpoint. *If local data is not available, transfer values from US following the same method as used for VSL.*

5) From mortality analysis, have or link to:

a) Change in annual average $PM_{2.5}$ or PM_{10} concentration ($\mu g/m^3$).

i) If ozone concentrations are available, those may be used as well.

ii) The morbidity risks for all endpoints given in Appendix A can be calculated with an equation form that ignores absolute pollutant concentration, so background $PM_{2.5}$ concentration is not needed.

iii) Many endpoints are acute effects related to changes in daily 24-hour mean $PM_{2.5}$ rather than annual average, but calculations are simplified to annual changes due to resolution of available data. See Sensitivity Case 1.

b) Size of total exposed population, and share of exposed population in age categories of interest.

i) If age category data is missing or incomplete, annual national-level age composition data from 1950-2100 is available from the UN World Population Prospects website[17]. Note which revision year is used.

c) Economic index, if valuation is included.

6) Calculate change in incidence of each endpoint resulting from concentration change.

a) For concentration-response functions of the most common log-linear form, incidence y is expressed as $y=Be^{\beta x PM}$ or $\ln(y)= \alpha+\beta*PM$ (α incorporates all other independent variables

14 US Environmental Protection Agency. (2013). User's Manual for the Co-Benefits Risk Assessment (COBRA) Screening Model, Version 2.61.US EPA, Climate Protection Partnerships Division, State and Local climate and Energy Programs. Retrieved from http://epa.gov/statelocalclimate/documents/pdf/cobra-2.61-user-manual-july-2013.pdf.

15 Abt Associates Inc. (2012). BenMAP Environmental Benefits Mapping and Analysis Program, User's Manual Appendices. Research Triangle Park, US; Office of Air Quality Planning and Standards, US EPA. http://www.epa.gov/air/benmap/models/BenMAPAppendicesOct2012.pdf

16 US Environmental Protection Agency. (2006). 2006 National Ambient Air Quality Standards for Particle Pollution, Regulatory Impact Analysis. Appendix H—Additional details on Benefits Methodologies. US Environmental Protection Agency. Retrieved from http://www.epa.gov/ttn/ecas/regdata/RIAs/Appendix%20H—Additional%20Details%20on%20Benefits%20Methodologies.pdf

17 United Nations. (2012). World Population Prospects: The 2012 Revision. Age composition: annual population by age groups—both sexes. United Nations, Department of Economic and Social Affairs. Population Division, Population Estimates and Projections Section. Retrieved from http://esa.un.org/wpp/Excel-Data/EXCEL_FILES/1_Population/WPP2012_POP_F15_1_ANNUAL_POPULATION_BY_AGE_BOTH_SEXES.XLS

affecting incidence). The change in incidence Δy due to change in concentration ΔPM is expressed as:

$$\Delta y = y_0 \times \left(1 - \frac{1}{\exp(\beta \times \Delta PM)}\right),$$

where y_0 is the baseline incidence.

b) For concentration-response functions with logistic form, incidence y at pollutant level PM is expressed as

$$y = \frac{\exp(\beta \times PM) \times \exp(\alpha \times Z)}{1 + \exp(\beta \times PM) \times \exp(\alpha \times Z)}.$$

The change in incidence Δy due to change in concentration ΔPM is expressed as:

$$\Delta y = y_0 \times \left(1 - \frac{1}{(1 - y_0) \times \exp(\beta \times \Delta PM) + y_0}\right)$$

c) For concentration-response functions of a linear form, where incidence y is expressed as y = α+β*PM, the change in incidence Δy due to change in concentration ΔPM is calculated as: Δy = β*ΔPM. In this form the baseline rate cancels out and is not needed.

7) Apply valuation. More details on economic steps given in Costs Memo.

EXAMPLE: ON-ROAD PRIMARY $PM_{2.5}$ EMISSIONS IN US CITIES

For this walkthrough, please follow along in the accompanying Excel file, "US Morbidity Walkthrough.xlsx"

1) Choose set of endpoints.

For this example we will include several endpoints from each category for a fairly comprehensive example. The list appears in the table below, which also notes the specific age groups and other limits on the population to be included.

a) Note which age categories each endpoint applies to.

b) Note endpoints with other restrictions, such as specific sensitive population or potential double-counting.

Table 1: Morbidity endpoints included in the US example, noting age group the endpoint applies to and other restrictions on the population group for which the endpoint is calculated.

Endpoint	Age groups	Restrictions
MEDICAL VISITS AND ACUTE ILLNESS		
Acute myocardial infarction (non-fatal)	18+	*survival rate of 93%
Hospital admissions (all respiratory)	65+	
Hospital admissions (asthma)	0-17	
Hospital admissions (cardiovascular)	18+	*cannot include AMI
Emergency room visits (asthma)	0-85+	
BRONCHITIS AND ASTHMA		
Chronic bronchitis	27+	*only among population without bronchitis, requires prevalence data
Lower respiratory symptoms	7-14	
ACTIVITY EFFECTS		
Minor restricted activity days	18-64	*Refer to days where activity restriction is not so severe that it causes a work loss, so it is acceptable to calculate both this endpoint and work loss days.
Work loss days	18-64	

The age breaks given by the groups here are: 7,9,11,14,18,27,65. Since the age categories given by UN data are 5-year bins, we will use slightly broader age categories for hospital asthma admissions (0-19) and lower respiratory symptoms (5-14); and slightly narrower age categories for cardiovascular hospital admissions (20+), chronic bronchitis (30+), MRADs and work loss days (20-64). See the highlighted cells in the US Morbidity Walkthrough spreadsheet, Baseline Incidence tab.

2) For each endpoint, find the equation form and coefficient(s) for the concentration-response (C-R) function.

For this case, we chose a coefficient from a single study, but Sensitivity Case 3 looks at the use of multiple studies to estimate the coefficient using random/fixed effects pooling. Looking at the details of the study to find the coefficient provides a good opportunity to double-check the age range and restrictions or coinciding ICD-9 classifications of any endpoints.

Table 2: Coefficient and form of concentration-response functions for morbidity endpoints used in US example.

Endpoint	Coefficient (Study)	Form
MEDICAL VISITS AND ACUTE ILLNESS		
Acute myocardial infarction (non-fatal)	0.00225 (Zanobetti et al., 2009)	Log-linear
Hospital admissions (all respiratory)	0.0007 (Kloog et al. 2012)	Log-linear
Hospital admissions (asthma)	0.002 (Babin et al. 2007)	Log-linear
Hospital admissions (cardiovascular)	Ages 18-64: 0.0014 (Moolgavkar, 2000) Ages 65+: 0.00071 (Peng et al. 2008)	Log-linear
Emergency room visits (asthma)	0.0056 (Mar et al. 2010)	Log-linear
BRONCHITIS AND ASTHMA		
Chronic bronchitis	0.013185 (Abbey et al. 1995)	Logistic
Lower respiratory symptoms	0.019012 (Schwartz and Neas 2000)	Logistic
ACTIVITY EFFECTS		
Minor restricted activity days	0.00741 (Ostro & Rothschild 1989)	Log-linear
Work loss days	0.0046 (Ostro 1987)	Log-linear

3) For each endpoint find the baseline incidence rate, or the number of cases of the endpoint per person and per year, for the given age category.

Values from the US are taken from the BenMAP Appendix D. In some cases the age range for which the incidence is reported is broader than the 5-year age categories used (e.g. one hospitalization rate, 0.00231, is given for ages 75-84 in the BenMAP appendix, which includes ranges 75-79 and 80-84). In those cases, the same rate is assumed across all age categories, rather than assuming a higher rate for older age categories. The incidence rates are converted to uniform units (per-capita rates) and given in the US Morbidity Walkthrough excel file.

4) If valuation is included, determine the COI or WTP value of each endpoint.

Valuation is not included in this walkthrough.

5) From mortality analysis, have or link to:

a) Change in annual average $PM_{2.5}$ or PM_{10} concentration (μg/m³).

b) Size of total exposed population, and share of exposed population in each age category.

c) Economic index, if valuation is included

This walkthrough considers the morbidity impacts of primary $PM_{2.5}$ from on-road transportation in urban areas in the US. The ambient concentration from primary $PM_{2.5}$ emissions from on-road vehicles are taken from baseline policy scenario in the Roadmap model (2014 update). These concentrations reflect the average change in concentration for urban-dwellers in a set of 238 US cities. Year 2000 population data for all cities is provided by Angel et al.[18] Population growth rates (assuming medium fertility assumptions) and age composition are given in UN World Population Prospects, 2012 revision[19],[20].

6) Calculate change in incidence of each endpoint resulting from concentration change. Note that baseline incidence y_0 is calculated as the product of per-capita incidence rate and population within study area.

a) For concentration-response functions of the most common log-linear form, incidence y is expressed as $y=Be^{\beta xPM}$ or $\ln(y)= \alpha+\beta*PM$ (α incorporates all other independent variables affecting incidence). The change in incidence Δy due to change in concentration ΔPM is expressed as:

$$\Delta y = y_0 \times \left(\frac{1}{\exp(\beta \times \Delta PM)}\right),$$

where y_0 is the baseline incidence.

All of the health endpoints in the "Medical Visits and Acute Effects" and "Activity Effects" categories in this example and follow this form. Endpoints are calculated for each age category and each year. The excel equation for each cell:

'External Inputs'!B46*$B7*(1-(1/EXP($B$27*'External Inputs'!B$7)))

Population in age category in year*Age-specific incidence rate (doesn't change by year)*(1-(1/EXP(Coefficient*Change in $PM_{2.5}$ concentration in year)))

b) For concentration-response functions with logistic form, incidence y at pollutant level PM is expressed as

$$y = \frac{\exp(\beta \times PM) \times \exp(\alpha \times Z)}{1 + \exp(\beta \times PM) \times \exp(\alpha \times Z)}$$

The change in incidence Δy due to change in concentration ΔPM is expressed as:

$$\Delta y = y_0 \times \left(\frac{1}{(1-y_0) \times \exp(\beta \times \Delta PM) + y_0}\right)$$

All of the health endpoints in the "Bronchitis and Asthma" category in this example follow this form. The excel equation for lower respiratory symptoms:

'External Inputs'!B43*$H4*(1-1/((1-$H4)*EXP(B152*'External Inputs'!B$7)+$H4))

Population in age category in year*Age-specific incidence rate (doesn't change by year)*(1-1/((1-Age-specific incidence rate)*EXP(Coefficient*Change in $PM_{2.5}$ concentration in year)+Age-specific incidence rate))

Chronic bronchitis has the additional restriction that the risk only applies to share of the population that is **not** already affected:

'External Inputs'!B48*(1-$P9)*$G9*(1-1/((1-$G9)*EXP($B$125*'External Inputs'!B$7)+$G9))

PIACIY*(1-Prevalence of endpoint)*ASIR*(1-1/((1-ASIR)*EXP(C*CiPMCiY)+ASIR))

c) For concentration-response functions of a linear form, where incidence y is expressed as $y = \alpha+\beta*PM$, the change in incidence Δy due to change in concentration ΔPM is calculated as: $\Delta y = \beta*\Delta PM$. In this form the baseline rate cancels out and is not needed.

There are no endpoints in this example that follow this form.

RESULTS:

Figures 2, 3, and 4 below show the annual cases of the nine morbidity endpoints that are attributable to primary $PM_{2.5}$ emissions from on-road vehicles in

18 Angel, S., J. Parent, D. L. Civco and A. M. Blei. (2010). Atlas of Urban Expansion, City Database. Cambridge MA: Lincoln Institute of Land Policy. Retrieved from http://www.lincolninst.edu/subcenters/atlas-urban-expansion/documents/universe-of-cities-data.xls

19 United Nations. (2012). World Population Prospects: The 2012 Revision. Population Growth Rate. United Nations, Department of Economic and Social Affairs. Population Division, Population Estimates and Projections Section. Retrieved from http://esa.un.org/wpp/Excel-Data/EXCEL_FILES/1_Population/WPP2012_POP_F02_POPULATION_GROWTH_RATE.XLS

20 United Nations. (2012). World Population Prospects: The 2012 Revision. Annual Population by Age Groups—Both Sexes. United Nations, Department of Economic and Social Affairs. Population Division, Population Estimates and Projections Section. Retrieved from http://esa.un.org/wpp/Excel-Data/EXCEL_FILES/1_Population/WPP2012_POP_F15_1_ANNUAL_POPULATION_BY_AGE_BOTH_SEXES.XLS

urban areas in the United States. The annual totals are also provided in the Results tab in the US Morbidity Walkthrough. After a monetary value is assigned to each endpoint, the total economic benefits of reduced morbidity can be summed and included in a cost-benefit analysis.

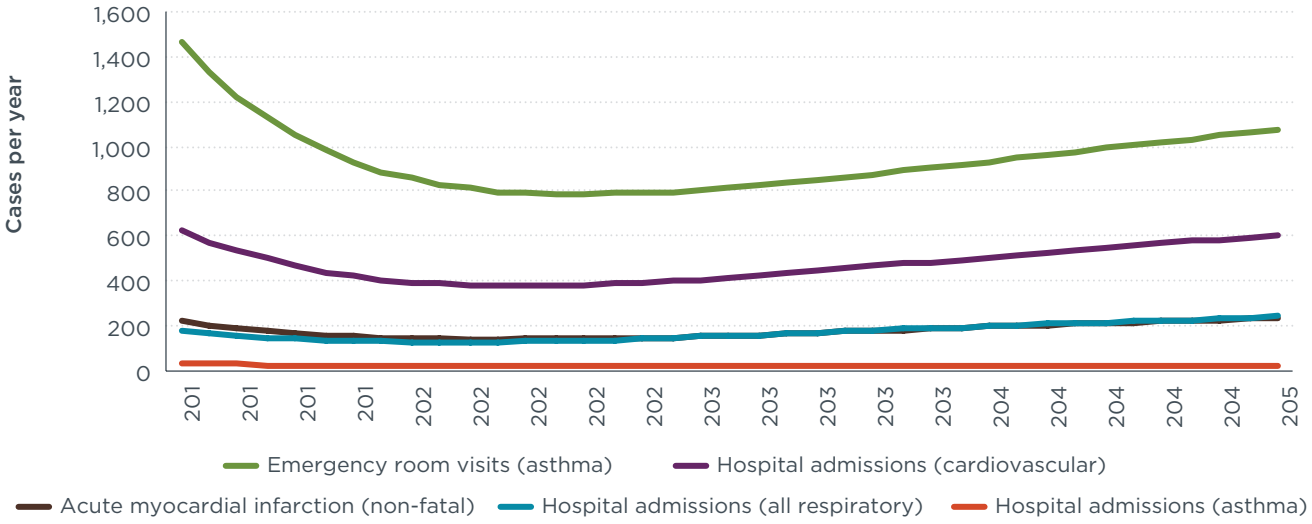

Figure 2: Medical visits and acute illness due to urban on-road transportation emissions of primary $PM_{2.5}$ in the United States

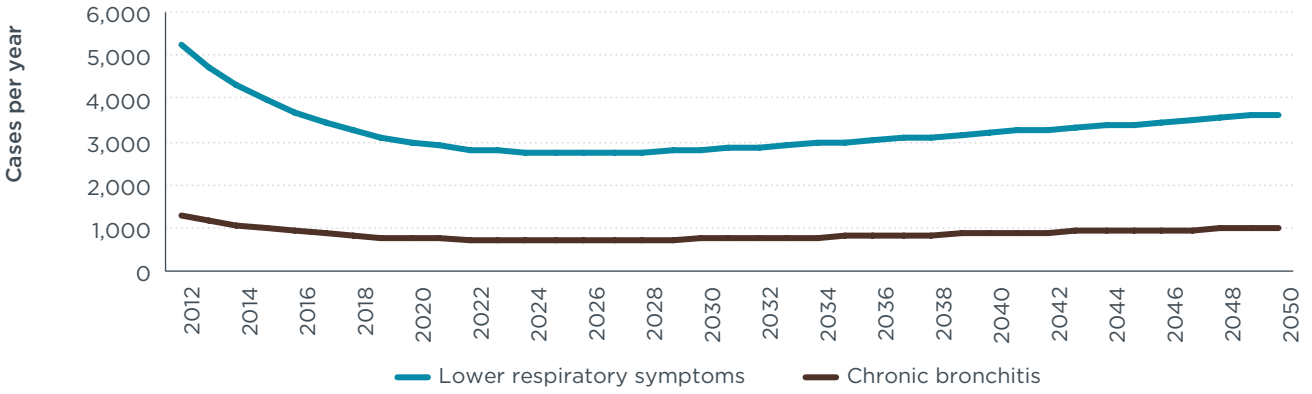

Figure 3: Bronchitis and asthma due to urban on-road transportation emissions of primary $PM_{2.5}$ in the United States

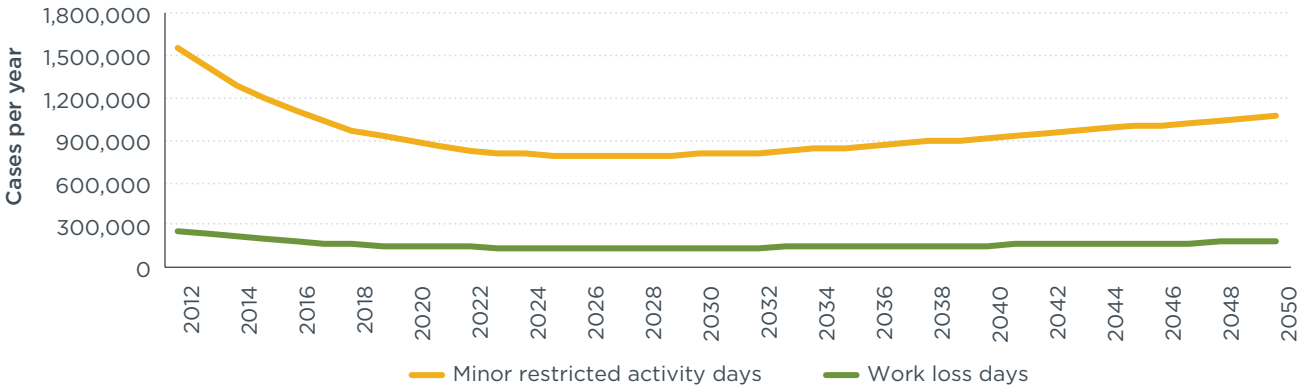

Figure 4: Activity effects of urban on-road transportation emissions of primary $PM_{2.5}$ in the United States

Appendix A. Choosing endpoints

Many epidemiological studies have been conducted over the last three decades to estimate the relationship between particulate matter and a wide variety of morbidity endpoints[21],[22],[23]. There is not currently any standard set of morbidity endpoints recommended by the World Health Organization, the US Environmental Protection Agency, or other authorities. As can be seen in Table 6 in Appendix D, recent health impact assessments have varied in the endpoints considered, and sometimes include similar but distinct endpoints with C-R functions based on different epidemiological studies (e.g. asthma attacks or asthma exacerbation).

The ICCT does not adopt a standard set of morbidity endpoints, but recommends choosing from the studies included in Appendix D of the BenMAP Manual. This appendix includes summaries of peer-reviewed studies conducted in the US, and is updated periodically. A list of these endpoints is provided in Table 3.

Table 3: Description of commonly used morbidity endpoints (from US EPA 2013 "User's Manual for the Co-Benefits Risk Assessment (COBRA) Screening Model")

Health Effect	Description
Mortality	Number of deaths
Chronic bronchitis	Cases of chronic bronchitis
Non-fatal heart attacks	Number of non-fatal heart attacks
Respiratory hospital admissions	Number of cardiopulmonary-, asthma, or pneumonia-related hospitalizations
Cardiovascular-related hospital admissions	Number of cardiovascular-related hospitalizations
Acute bronchitis	Cases of acute bronchitis
Upper respiratory symptoms	Episodes of upper respiratory symptoms: runny or stuffy nose; wet cough; and burning, aching, or red eyes
Lower respiratory symptoms	Episodes of lower respiratory symptoms: cough, chest pain, phlegm, or wheeze
Asthma emergency room visits	Number of asthma-related emergency room visits
Minor restricted activity days (MRAD)	Number of minor restricted activity days (days on which activity is reduced but not severely restricted; missing work or being confined to bed is too severe to be MRAD).
Workdays lost	Number of workdays lost due to illness

Table 4 summarizes the expert evaluation of the weight of evidence for various endpoints. The expert organizations included are the American Heart Association,[24] the Health Effects Institute,[25] the US EPA,[26],[27] and the World Health Organization.[28],[29],[30] These organizations and agencies have published reviews and meta-analyses of health impacts from air pollution within the last 15 years. The organizations and agencies came to varying, but generally similar, conclusions about the state of the science on and the strength of association between the health effects of air pollution and particulate matter. The table is set up according to a "tiered" classification system, in which, generally speaking, the endpoints with the strongest support from the epidemiological evidence at the time are labeled "Tier 1," those with moderate support from the epidemiological evidence are labeled "Tier 2," and those with the least, but still some, support from the epidemiological evidence are labeled "Tier 3." For the endpoints taken from the WHO working group paper (2000; 2005), there was no ascending classification of the epidemiological evidence for the endpoints chosen. All effects listed in this paper were placed under Tier 1 because these endpoints were listed as definitively associated with air pollution exposure.

21 Health Effects Institute. (2003). Revised Analyses of Time-Series Studies of Air Pollution and Health. Health Effects Institute, Special Report. Retrieved from http://pubs.healtheffects.org/getfile.php?u=21

22 Health Effects Institute. (2004). Health Effects of Outdoor Air Pollution in Developing Countries of Asia: A Literature Review. Health Effects Institute, Special Report 15. Retrieved from http://pubs.healtheffects.org/getfile.php?u=13

23 Pope, C. A., & Dockery, D. W. (2006). Health effects of fine particulate air pollution: lines that connect. *Journal of the Air & Waste Management Association*, 56(6), 709–742.

24 Brooks et al. (2010). Particulate Matter Air Pollution and Cardiovascular Disease: An Update to the Scientific Statement From the American Heart Association. *Circulation*; 121:2331-2378.

25 Health Effects Institute (HEI). (2010). Special Report 17: Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects. Retrieved from http://pubs.healtheffects.org/getfile.php?u=553

26 Environmental Protection Agency (EPA). (2009). Integrated Science Assessment for Particulate Matter.

27 Environmental Protection Agency (EPA). (2012). Provisional Assessment of Recent Studies on Health Effects of Particulate Matter Exposure.

28 World Health Organization (WHO) Working Group. (2000). Quantification of the Health Effects of Exposure to Air Pollution.

29 World Health Organization (WHO). (2006). Air Quality Guidelines: Global Update 2005 (Particulate matter, ozone, nitrogen dioxide and sulfur dioxide).

30 Lim et al. (2013). A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990-2010: a systematic analysis for the Global Burden of Disease Study 2010. *The Lancet* 380:2224-2260.

Table 4: Summary of the science regarding the morbidities associated with air pollution and $PM_{2.5}$ exposure

	AHA (2010)	HEI (2010)	EPA PM-ISA (2009; 2012)	GBD (2013)	WHO (2000; 2005)
Tier 1	Ischemic heart disease, both fatal and nonfatal events	Exacerbation of respiratory symptoms in asthmatic children	Cardiovascular effects (strongest effect in older, postmenopausal women, specifically for stroke, incident myocardial infarction, incident hypertension)	Ischemic heart disease Lower respiratory disease Chronic obstructive pulmonary disease Trachea/ bronchus/ lung cancer Cerebrovascular disease	Chronic respiratory disease incidence and prevalence (including asthma, chronic obstructive pulmonary disease, chronic pathological changes) Chronic change in physiologic function Lung cancer Chronic cardiovascular disease Reproductive outcomes: pregnancy complications (including fetal death), low birth weight, pre-term delivery, intrauterine growth retardation, small for gestational age
Tier 2		Asthma incidence and prevalence in children	Respiratory effects (lung function, respiratory symptoms and hospitalizations, asthma development/ incidence)		
Tier 3	Cardiovascular hospitalizations Heart failure, Ischemic stroke, both fatal and nonfatal events Vascular disease (deep venous thrombosis only) Cardiac arrhythmia/ cardiac arrest	Acute myocardial infarction and atherosclerosis Lung function Exacerbation of respiratory symptoms in adults	Reproductive and developmental outcomes (specifically reduced birth weight) Cancer, mutagenicity, and genotoxicity outcomes		

Appendix B. Sensitivity Case 1: Annual average $PM_{2.5}$ vs. 24-hour average $PM_{2.5}$

Many morbidity endpoints are acute effects—short-term medical issues that take place in a single day (respiratory symptom days, work loss days, emergency room visits) or over a period of less than a week (hospitalization). Epidemiology studies for acute effects often estimate changes in risk based on daily pollutant concentrations, and the concentration-response functions from those studies are based on daily exposure (24-hour mean concentration) rather than annual exposure. However, in most cases there is not enough available information about baseline incidence rates and reductions in emissions to model daily changes in morbidities. Instead of modeling day-to-day variation in incidence and exposure, the change in **annual** $PM_{2.5}$ concentration coupled with **annual** incidence rates is used with risk estimates based on 24-hour concentrations. EPA sources note that the results will generally be insensitive to the use of annual mean or daily 24-hour mean values because most of the health impact functions in BenMAP are log-linear, and approximately linear within the range of exposure that U.S. populations experience[31]. This sensitivity case considers an environment with a much wider range of exposure than is typical for the US, and calculates the variation in impact estimates caused by substituting annual change for daily change in $PM_{2.5}$.

The US Department of State has published daily monitoring data from Beijing for the years 2008-2014[32]. The 24-hour mean concentrations for the year 2012 are summarized in Figure 5.

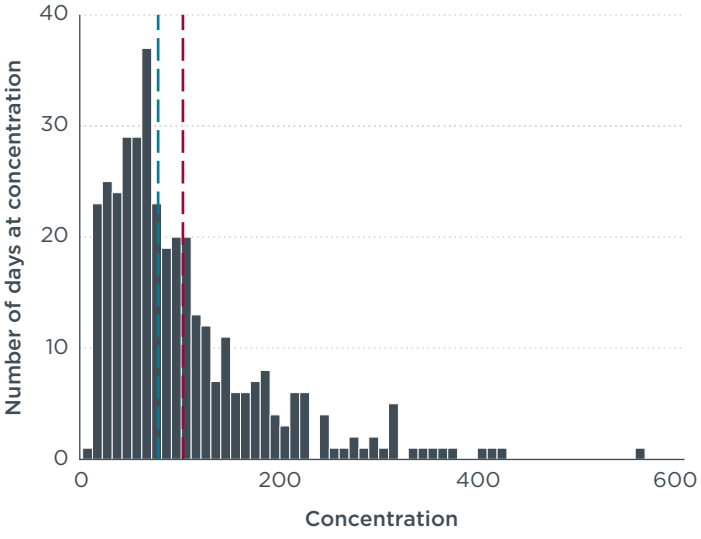

Figure 5: Histogram showing the distribution of 24-hour $PM_{2.5}$ concentrations in Beijing throughout the year 2012. The dashed blue line shows the mean concentration (102 μg/m³), and the dashed red line shows the median concentration (77 μg/m³).

The split between mean and median reflects the skewed distribution of concentrations; concentrations exceeded the mean of 102 μg/m³ in only 35% of days, but reached values exceeding 400 μg/m³.

Four scenarios are considered that utilize the daily resolution of the concentration data and compare the results against those calculated for an annual average concentration reduction. The first two scenarios consider a relatively small, consistent reduction in $PM_{2.5}$ concentrations. These reductions are similar to what might be achieved through new vehicle emission standards. For example, the Roadmap model projects a change of 1.2 μg/m³ in urban $PM_{2.5}$ concentration from more stringent emission standards for on-road vehicles in China (comparing the year 2010 with 2030). This reduction would be assumed to occur consistently on all days throughout the year. To mimic this pattern, Scenario 1 assumes a uniform reduction of 2.5 μg/m³ each day. Scenario 2 assumes the same average annual reduction of 2.5 μg/m³ with moderate variation in daily concentration reductions. The reductions in each day were randomly generated from a normal distribution with a mean of 2.5 that range from 0 to 5.

The third and fourth scenarios consider larger, more variable daily reductions down to a threshold concentration. These reductions are more similar to what might be achieved by policies focusing on preventing exceedance of daily air quality standards. An example of such a policy is a more drastic form of Spare the Air days/nights where strict limitations are placed on vehicle and industry activity during periods of high pollution. Scenario 3 models a reduction in daily concentration down to 25 μg/m³ each day and Scenario 4 models a reduction to 10 μg/m³. These scenarios result in reductions that vary by day and share the same skewed distribution as the underlying concentration. The reduction in health impacts from meeting the 25 and 10 μg/m³ limit each day are compared against the reduction estimated by reducing the annual average concentration to 25 and 10 μg/m³. The annual calculation implicitly assumes that the same average reduction takes place each day—reductions of 77 and 92 μg/m³ in Scenario 3 and 4, respectively—and is not sensitive to the varied patterns of daily pollution that include some days that do not exceed the limits and some days of extreme exceedance. The frequency of these boundary cases is shown in Table 4[33].

31 Neal Fann, personal communication

32 US Department of State. (2014). Beijing 2012 HourlyPM2.5_created20140325.csv. *Mission China: Beijing—Historical Data*. Retrieved from http://www.stateair.net/web/historical/1/1.html

33 The value of 200 μg/m³ was chosen to illustrate an exceedance value that falls within the range of concentrations where the exposure-response function behaves non-linearly; the specific value of 200 is not a meaningful threshold.

Table 5: For Beijing air quality in the year 2012, number of days that the 24-hr average concentration was below 25 or 10 μg/m³, and days that the 24-hr average concentration exceeded those limits by >200 μg/m³

	Days not exceeding $PM_{2.5}$ limit	Days of extreme exceedance (>200 μg $PM_{2.5}$ over limit)
S3: Meeting 25 μg/m³ limit	37	29
S4: Meeting 10 μg/m³ limit	1	38

A single health endpoint was chosen for this sensitivity case: Emergency Room visits due to asthma. This endpoint uses the typical log-linear exposure-response function, so other endpoints can be expected to follow a similar pattern. Although data tracking daily ER admissions for asthma may exist for Beijing in 2012, such data were not easily accessible for this work and may require substantial effort to obtain and prepare. In lieu of such data, the annual hospitalization rate for asthma used in the US was divided evenly across all days of the year. The same city population was assumed for the entire year.

RESULTS

The results for the four scenarios are shown in Table 5. In the first scenario, all variables used in calculating change in incidence are uniform across all days for the first scenario (pollution change, population, hospitalization rate), so there is no reason to expect the sum of the daily calculations to vary from the annual calculation. Indeed, it does not. In the second scenario there is daily variation in the $PM_{2.5}$ reductions but the mean is nearly the same as the uniform reduction in Scenario 1. The daily and annual results in Scenario 2 differ by <0.2%; daily variations of a relatively low magnitude do not significantly alter the results.

Table 6: Reductions in ER visits for asthma in Beijing in the three scenarios

	Daily Calculation (total cases reduced)	Annual Calculation (total cases reduced)	Avg daily reduction (μg/m³)	Maximum daily reduction (μg/m³)
S1: Uniform daily reduction of 2.5 μg/m³	1,364	1,364	2.5	2.5
S2: Randomly varied reduction averaging 2.5 μg/m³ per day	1,362	1,364	2.5	5.0
S3: Meeting 25 μg/m³ limit	29,105	34,239	77.3 in daily 76.7 in annual	543.6
S4: Meeting 10 μg/m³ limit	34,304	39,386	91.7	558.6

In the third and fourth scenario the annual calculation predicted 18% and 15% greater reductions than the daily calculation. This difference is caused in part by the pattern shown in Figure 2: the log-linear concentration-response function (brown line) is approximately linear within the range of concentrations experienced within the US (0-50 μg/m³) but it curves at concentrations experienced on extreme days in China. As a consequence, the number of cases reduced per unit $PM_{2.5}$ reduced (blue line) decreases as the total change in $PM_{2.5}$ increases. In Scenarios 3 and 4 there are some days with extreme reductions in concentrations that result a lower number of cases reduced per unit PM reduced. In addition, there are 37 days in Scenario 3 where no impacts are modeled to occur, further reducing the estimates from the daily calculation.

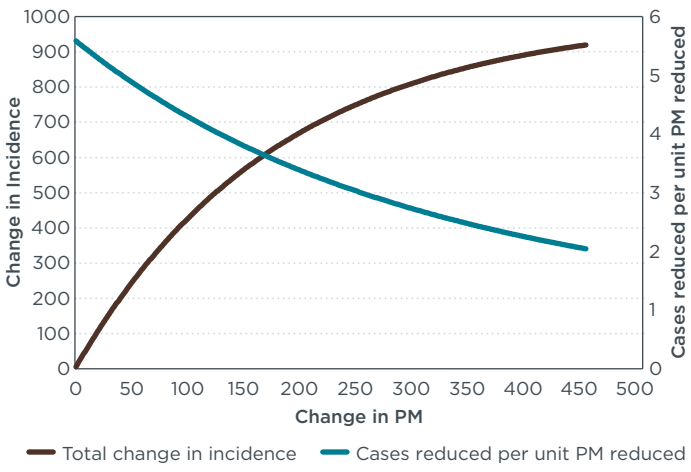

Figure 6: The change in incidence of ER visits for asthma due to different changes in $PM_{2.5}$ concentration, assuming a baseline incidence of 1000 cases/year. The underlying concentration-response function is log-linear and has a coefficient of 0.0056 based on Mar et al. (2010).

CONCLUSIONS

This sensitivity analysis shows that with a log-linear concentration-response function, the impact estimated from daily $PM_{2.5}$ reductions that vary within a range from 0-5 μg/m^3 does not differ significantly (<0.2%) from the impact estimated from a single annual calculation. The type of policies that the ICCT has modeled in the past result in concentration reductions within this range, so it is acceptable to apply daily concentration-response functions to annual reductions. This sensitivity analysis does not include variation in the daily hospitalization rate—sensitivity may vary if daily hospitalization rates are not uniform.

When a policy targets days of exceedance rather than causing a consistent daily reduction, the use of an annual calculation may result in an overestimation compared with the sum of daily impacts. This is a consequence of the use of the log-linear concentration-response function in a range of concentrations where it does not behave linearly: given two 1-week periods where the first includes 6 days of no exceedance and one extreme exceedance (where non-linear behavior occurs) and the second includes 7 days of low/moderate exceedance, the log-linear function will estimate a greater change in incidence per μg/m^3 in the second week. For this reason, annual approximations of daily health-impact functions should be used with caution in cities where daily concentrations exhibit high variation and maximum concentrations above the "approximately linear" range of concentration-response functions (in this case, 0-50 μg/m^3).

Appendix C. Sensitivity Case 2: Variation among local and transferred incidence rates

Because morbidity incidence rates are not easily available in most developing countries, a simplified health impact analysis may substitute baseline incidence rates from other regions and note this substitution among the sources of uncertainty in the analysis. A literature review found that baseline incidence from the US, Canada, and EU is frequently substituted for incidence in developing countries but in a few cases local incidence was provided (see paragraph 2 on page 2). It might be assumed that incidence rates in developing countries would be more similar to each other than to those in developed countries. This sensitivity analysis explores that assumption, but does not reach a conclusive recommendation for best practices in transferring incidence rates.

Among the incidence rates drawn from the literature, only a subset were comparable. Incidence used by Cesar et al.[34] for the five endpoints shown in Table 6 can be compared with the US incidence data provided in BenMAP[35]. A third source, Guttikunda and Goel[36], also used local morbidity rates, but did not report them directly. Instead they reported the coefficient for a linearized concentration response function, with units of effects per capita per μg/m³. These are calculated from a log-linear function as:

$$\Delta y = y_0 \times \left(1 - \frac{1}{e^{\beta}}\right)$$

where both y and y_0 are per-capita. They are calculated from a logistic function as:

$$\Delta y = y_0 \times \left(1 - \frac{1}{(1 - y_0) \times e^{\beta} \times y_0}\right)$$

Incidence in the US and Mexico was converted to this form using the concentration-response functions given in the footnotes to Table 6. It is likely that many of the concentration-response functions differ from those used by Guttikunda and Goel, which detracts from the comparison. More information is being sought from the authors, and corrections will be made if that information is made available. Where age-specific incidence was given, values were adjusted to match the age structure in India in the year 2010.

Table 7: Comparison of linearized concentration-response function parameters

Health Impact	Effects per capita per μg/m³		
	GUTTIKUNDA AND GOEL 2013	US (BENMAP), AGE-ADJUSTED	MEXICO (CESAR ET AL. 2002), AGE-ADJUSTED
Adult chronic bronchitis[1]	0.000040	0.000106	0.000198
Respiratory hospital admission[2]	0.000012	0.000003	0.000003
Cardiac hospital admission[3]	0.000005	0.000006	0.000006
Emergency room visit[4]	0.000235	0.000022	0.000018
Restricted activity days[5]	0.038280	0.057584	0.057584

1 Abbey, D.E., B.L. Hwang, R.J. Burchette, T. Vancuran and P.K. Mills. (1995). Chronic Respiratory Symptoms Associated with Estimated Long-Term Ambient Concentrations of Fine Particulates Less than 2.5 Microns in Aerodynamic Diameter (PM2.5) and Other Air Pollutants. *Journal of Exposure Analysis and Environmental Epidemiology* 5(2):137-159.

2 Kloog, I., B.A. Coull, A. Zanobetti, P. Koutrakis, J.D. Schwartz. (2012). Acute and Chronic Effects of Particles on Hospital Admissions in New England. *PLoS ONE* 7(4):1-8.

3 Moolgavkar, S.H. (2000). Air pollution and hospital admissions for diseases of the circulatory system in three U.S. metropolitan areas. *Journal of Air and Waste Management Association* 50(7):1199-206.

4 Tolbert, P.E., M. Klein, et al. (2007). Multipollutant modeling issues in a study of ambient air quality and emergency department visits in Atlanta. *Journal of Exposure Science and Environmental Epidemiology* 17 Suppl. 2: S29-35.

5 Ostro, B.D. (1987). Air Pollution and Morbidity Revisited: A Specification Test. *Journal of Environmental Economics and Management* 14:87-98.

As can be seen in Figure 7, the values from BenMAP and Cesar et al. are much more similar to each other than they are to the values from Guttikunda and Goel. This is likely due to the fact that the two former sets of values were calculated with the same concentration-response functions. This suggests that the per-capita impacts are much more sensitive to the choice of concentration-response function than to baseline incidence, but this cannot be concluded without more information from Guttikunda and Goel. The exception to this pattern is the Adult Chronic Bronchitis endpoint, for which it is likely that the same C-R function was used across all three studies. In this case, per-capita effects vary by a factor of 5 among the two developing countries but only by a factor of 2-3 between developing countries and the US; still, this comparison across three data points does not provide a conclusive answer to the question of whether transferring incidence data from a high-income country to a developing country produces less accurate estimates than transferring incidence data from another developing country. Further analysis is recommended as more incidence data becomes available.

34 Cesar H. et al. (2002). Improving air quality in metropolitan Mexico City: an economic valuation, Vol. 1. World Bank, Policy Research working paper series; no. WPS 2785. Retrieved from http://go.worldbank.org/06R8X8GXN0

35 Abt Associates Inc. (2012). BenMAP Environmental Benefits Mapping and Analysis Program, User's Manual, Appendix D: Health Incidence & Prevalence Data in the U.S. Setup. Research Triangle Park, US; Office of Air Quality Planning and Standards, US EPA. http://www.epa.gov/air/benmap/models/BenMAPAppendicesOct2012.pdf

36 Guttikunda S.K., and R. Goel. (2013). Health impacts of particulate pollution in a megacity—Delhi, India. *Environmental Development* 6 (2013) 8-20.

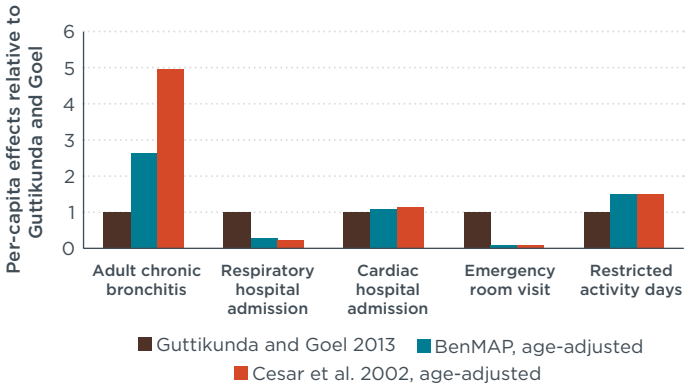

Figure 7: Comparison of linearized concentration-response function parameters

Appendix D

Table 8: Cross-study comparison of annual total mortality and morbidity events

Mortality							
	DELHI	**COAL KILLS**	**WB DASEC**	**BELL**	**CAFE (MTFR)**	**CAAA (2020)**	**HAPINZ**
Adult	16,200	115,000	109,340	152,982	81,400	160,000	2,307
Child/Infant	0	10,000	7,513	3,768	100	230	9

Morbidity							
	DELHI	**COAL KILLS**	**WB DASEC**	**BELL**	**CAFE (MTFR)**	**CAAA**	**HAPINZ**
Acute bronchitis	391,500	0	0	142,338	0	180,000	0
Chronic bronchitis	53,500	170,000	48,483	47,903	38,500	75,000	0
Hospital admissions	24,700	0	372,331	82,726	20,700	135,000	1,180
Medical visits (children)	0	0	0	303,238	0	0	0
ER visit	483,200	900,000	7,303,897	713,282	0	120,000	0
Non-fatal myocardial infarction	0	0	0	0	0	200,000	0
Chest discomfort	0	8,400,000	0	0	0	0	0
School loss days	0	0	0	0	0	5,400,000	0
Work loss days	0	0	0	8,297,014	0	17,000,000	0
Respiratory medication use	0	0	0	0	6,900,000	0	0
Asthma exacerbation	0	0	0	0	0	2,400,000	0
Asthma attack	6,000,000	20,900,000	0	4,286,250	0	0	0
Lower respiratory illness (children)	0	0	16,255,360	0	0	0	0
Respiratory symptom days	244,600,000	625,000,000	3,917,855,052	0	89,600,000	4,300,000	0
Restricted activity	51,200,000	160,000,000	1,231,020,030	23,922,198	67,000,000	110,000,000	2,926,500

Table 9: Cross-study comparison of annual societal cost of mortality and morbidity

Mortality					
	USD	**Rs.**	**Euro**	**2006 USD**	**USD**
	COAL KILLS	**WB DASEC**	**CAFE (MTFR)**	**CAAA (2020)**	**HAPINZ**
Adult	4,600	1,018,000	163,983	1,700,000	8,211
Child/Infant	420	13,000	300	2,500	31
Mortality	5,020	1,031,000	164,283	1,702,500	8,242

Morbidity					
	COAL KILLS	**WB DASEC**	**CAFE (MTFR)**	**CAAA**	**HAPINZ**
Acute bronchitis	0	0	0	94	0
Chronic bronchitis	170	1,000	7,219	36,000	0
Hospital admissions	0	3,000	42	3,100	6
Medical visits (children)	0	0	0	0	0
ER visit	60	8,000	0	44	0
Non-fatal myocardial infarction	0	0	0	21,000	0
Chest discomfort	35	0	0	0	0
School loss days	0	0	0	480	0
Work loss days	0	0	0	2,700	0
Respiratory medication use	0	0	7	0	0
Asthma exacerbation	0	0	0	90	0
Asthma attack	420	0	0	0	0
Lower respiratory illness (children)	0	14,000	0	0	0
Respiratory symptom days	1,200	0	3,440	102	0
Restricted activity	1,600	46,000	5,589	6,700	181